Driving forces of global wildfires over the past millennium and the forthcoming century

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Recent bursts in the incidence of large wildfires worldwide have raised concerns about the influence climate change and humans might have on future fire activity. Comparatively little is known, however, about the relative importance of these factors in shaping global fire history. Here we use fire and climate modeling, combined with land cover and population estimates, to gain a better understanding of the forces driving global fire trends. Our model successfully reproduces global fire activity record over the last millennium and reveals distinct regimes in global fire behavior. We find that during the preindustrial period, the global fire regime was strongly driven by precipitation (rather than temperature), shifting to an anthropogenic-driven regime with the Industrial Revolution. Our future projections indicate an impending shift to a temperature-driven global fire regime in the 21st century, creating an unprecedentedly fire-prone environment. These results suggest a possibility that in the future climate will play a considerably stronger role in driving global fire trends, outweighing direct human influence on fire (both ignition and suppression), a reversal from the situation during the last two centuries.

biomass burning | fire modeling | human–environment interactions | paleoclimate

Once viewed as local phenomena, fires are now recognized as a global scale environmental process that has influenced the atmosphere and biosphere for hundreds of millions of years (1, 2). Today fires continue to directly influence human society and affect global climate. With a recent rise in the incidence of large uncontrolled fires, occurring regardless of national fire-fighting capacities (1, 3–7), concerns have grown about how climate change and human activities might impact future fire regimes. However, it is still unsettled whether climate or direct anthropogenic influence (fire ignition and suppression) are more important in determining global fire trends (1).

Recently we have developed a fire representation method for global climate models (8). We utilize it here for an attempt to reproduce past millennium fire activity trends and separate climatic and anthropogenic effects. The method estimates fire activity based on vegetation density, ambient meteorological conditions (temperature, relative humidity, and precipitation), availability of ignition sources (lightning and anthropogenic), and fire suppression rates. We base our historical estimates on simulations of 850–2003 CE (common era) climate conditions using the AR4 version of the Goddard Institute for Space Studies (GISS) general circulation model (GCM) (9, 10), and land-use and population density reconstructions from the History Database of the Global Environment (HYDE) 3.1 (11). The simulated climate variations and land-use changes are used to estimate baseline fire activity trends [assuming ubiquitous ignition source distribution (8)] without any direct human interference. Population densities are used to assess direct anthropogenic effects (fire ignition and suppression, both increasing with population density), assuming fire suppression effectiveness to increase with time. *Materials and Methods* and *SI Text* provide further details on the simulations setup.

Results

Past Fire Activity. Model results successfully recreate global fire activity variations reconstructed from sedimentary charcoal records (12) (Fig. 1*A*). Until the late 18th century, simulations either with or without direct anthropogenic influence agree well with reconstructed data, suggesting that during this period global fire activity was primarily climate-driven, whereas human influence remained relatively small. Although this is in general agreement with the charcoal data interpretation (12), we find that changes in global precipitation, rather than temperature, played a major role in determining global fire activity variations in the preindustrial period (*SI Text*). For instance, the cold and dry climate during the late 15th century Spörer Minimum (Fig. 1*B*) corresponds with increased global fire activity (in both the model-based and the charcoal-based reconstruction), whereas during the cold but humid Maunder Minimum (17th–early 18th centuries) global fire activity decreased. In the same epoch, sharp native population declines in both the Americas, following the European conquest, led to a decreased number of human-induced (but not "natural") fires on these continents. However, because the overall anthropogenic influence on global fires was weak then, the estimated global effect of these changes was relatively small (Fig. 1*A*).

Following the Industrial Revolution (late 18th–early 19th centuries), human population expanded rapidly (Fig. 1*C*). Unprecedented rates of fossil fuel burning led to the onset of global warming (Fig. 1*B*). Over the 19th century both the model- and the charcoal-based records show sharp increases in biomass burning (Fig. 1*A*). Although changing climate and increasing population both contributed to this rise, model results suggest a stronger influence from direct anthropogenic activities, which in the 19th century became the dominant driver of global fire activity trends (*SI Text*). Expanding human population induced rapid land-use changes. Forests were cleared for agricultural land and pastures, reducing vegetation density (Fig. 1*C*), and hence the fuel amounts, slowing fire activity's long-term rise. However, the common tool for land clearing was fire (13–16). Wildfire mapping for the 1880 US census, for instance, revealed staggering amounts of burning, predominantly of agricultural origins (15). Hence the land-clearing process itself could have boosted the number of fires in the early Industrial Period, contributing to the earlier increase of fire activity in the charcoal-based record. Extensive information on the worldwide history of land-clearing fires (which are currently not depicted in our model) is necessary to credibly assess their effect on global fire activity variations. Methane fire emissions reconstructed from Antarctic ice-core

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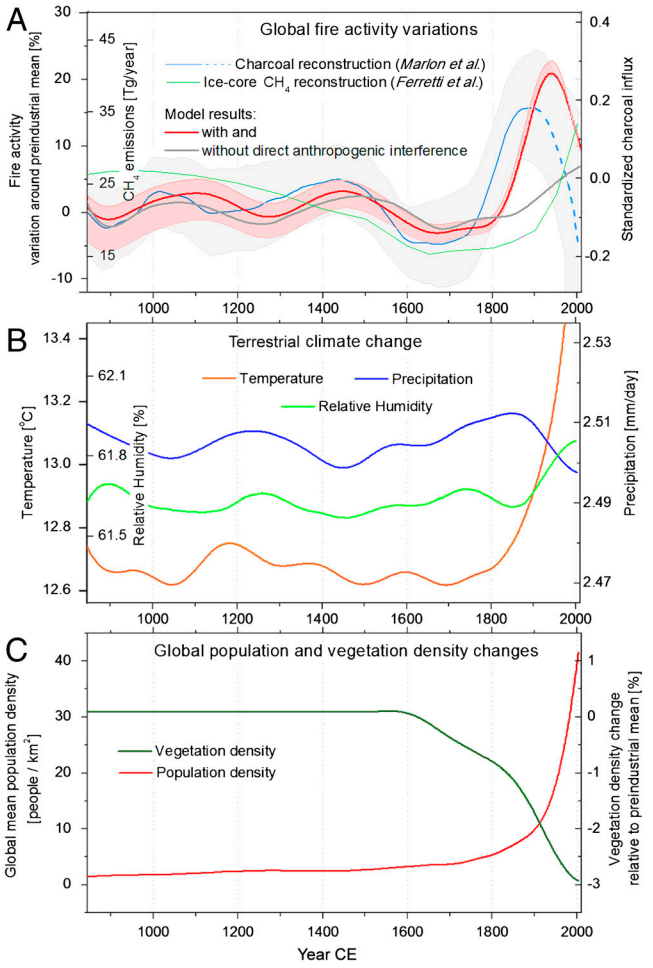

Fig. 1. Global fire activity, climate, vegetation, and population. (*A*) Modeled global fire activity variations (*SI Text*) with (red line) and without (gray line) direct anthropogenic influence (ignition and suppression): Red-shaded area represents uncertainty in the anthropogenic effect assumptions (*SI Text*); ice-core methane fire emissions reconstruction (green line) (17) and charcoal-based global fires reconstruction (blue line) with gray-shaded confidence interval (12) and blue dashed line indicating increased uncertainty in the late 20th century reconstructions. (*B*) GISS GCM annual means of the terrestrial area surface temperature (orange line), precipitation (blue line), and relative humidity (green line). (*C*) Global mean population (red line) and vegetation (green line) densities (11).

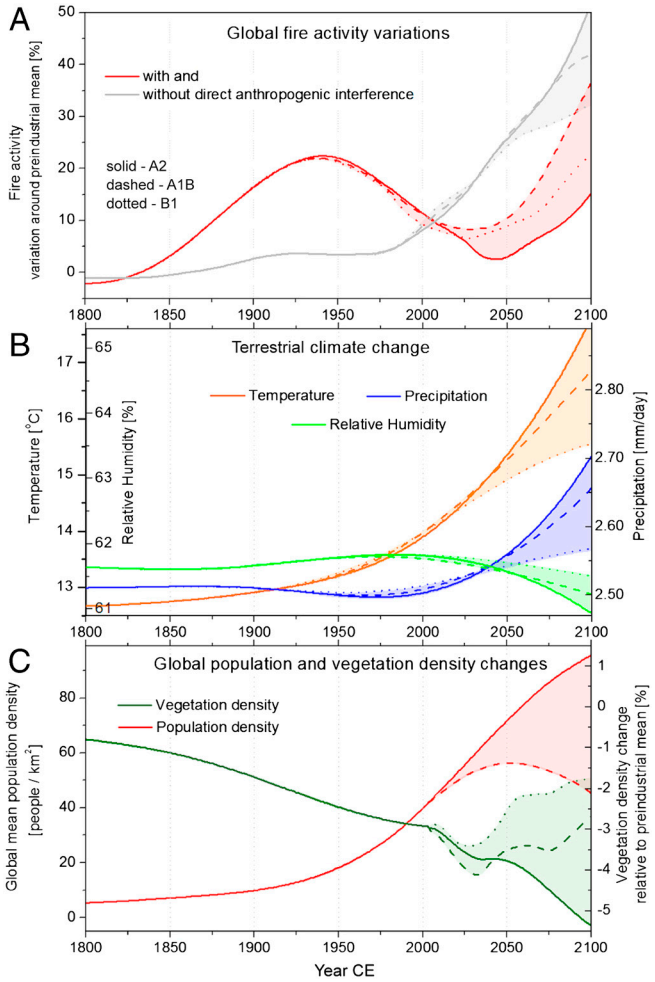

Fig. 2. Projected global fire activity, climate, vegetation, and population. Three SRES scenarios are shown: A2 ("maximum," continuing past variations with solid line), A1B ("midrange," dashed line), and B1 ("minimum," dotted line). (*A*) Modeled global fire activity with (red lines) and without (gray lines) direct anthropogenic interference; (*B*) GISS GCM annual means of the terrestrial surface temperature (orange lines), precipitation (blue lines), and relative humidity (green lines). (*C*) Global mean vegetation (green lines) and population (red lines) densities (A1B and B1 population scenarios coincide) (21).

records (17) suggest a later fire activity increase (Fig. 1*A*). Although some skepticism exists as to whether this trend reflects fire emissions (18), differences between the ice-core and the charcoal-based reconstructions illustrate uncertainties in past fire activity (though different smoothing procedures could enhance differences between these datasets).

Around 1900 there is a sharp downturn in global fire activity, both in the model- and the charcoal-based records, despite increasing temperatures and decreasing precipitation. In accord with the charcoal-based interpretations (12), this downturn results from increasing fire suppression (accompanying population growth), and decreased vegetation density, but with stronger influence from direct anthropogenic activity (*SI Text*). Toward the late 20th century, the charcoal-based records' uncertainty increases, and they do not depict, for instance, increased burning in the tropics and the western United States in the past three decades (12). Although ice-core reconstructions show an increasing trend throughout the 20th century, it is likely that the downturn in the charcoal-based data, reproduced by the model both on a global scale and at the charcoal sites (*SI Text*), is real, though late 20th century fire activity may be higher than implied by the charcoal-based records.

Future Fires. Overall, the model captures historical trends influenced by a variety of natural and anthropogenic factors remarkably well, inspiring some confidence in the model's projection of future fires. GISS GCM climate simulations (19), like other models, predict a significant warming over the forthcoming century (Fig. 2*B*). Rapidly rising temperatures and regional drying reverse the recent fire activity decline, driving a rapid increase after ~2050 in all three scenarios examined here, described in the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) (20, 21) (Fig. 2*A* and *SI Text*). Population growth, and to a lesser extent, land-cover change (Fig. 2*C*), reduces the increase in fire activity, but does not reverse the long-term trend, even in the A2 scenario where anthropogenic pressure is strongest and continues to increase throughout the simulations. Ironically the more "optimistic" A1B and B1 scenarios that produce milder warming result in greater biomass burning due to reversal of land conversion and declining population (and hence fire suppression).

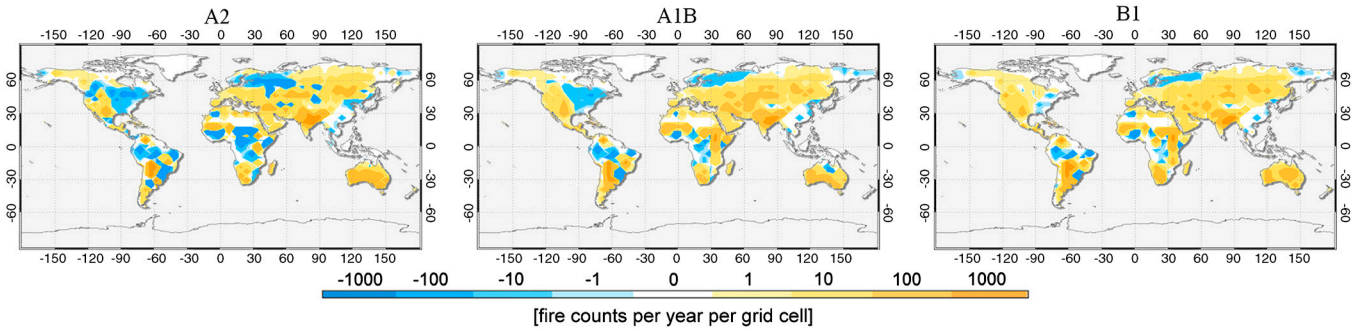

Fig. 3. Regional patterns of projected fire activity changes. Yellow shades indicate increases, and blue shades indicate decreases in linearized regional fire activity trends over the 21st century (years 2004–2100) in A2, A1B, and B1 scenarios.

Although global fire activity is projected to increase, this trend is not uniform worldwide. The broad spatial patterns of biomass burning trends are quite consistent across the scenarios (Fig. 3) and largely agree with another estimate (22). Less agreement is found with projections based on statistical relations between present-day climate and fires (23), which may be of limited value when applied to future climate due to shifting fire regime. Changes in the hydrologic cycle [some of which are robust features of climate models (24, *SI Text*)] play a large role in these projected regional variations, especially because temperatures rise nearly everywhere. Biomass burning trends in the United States (Fig. 4*A*) are a good example of the strong regional influence of hydrologic cycle changes. Although temperatures rise throughout the country, it becomes more humid and rainy in the East and drier in the West (Fig. 4*B*). Consequently, in the eastern United States fire activity declines, while rising considerably in the western United States (Fig. 4*A*). In both cases increasing population densities and land-cover changes (Fig. 4*C*) generally reduce fire activity. Our modeled 20th century eastern and western US trends agree fairly well with historical trends reconstructed for these regions by Mouillot and Field (25) (Fig. 4*A*). An exception is the first two decades of the century in the western United States, where the historical reconstruction shows increased burning, whereas our model indicates decreased fire activity. Although the historical reconstruction relies on data that are often too inconclusive to support consistent quantitative accuracy (25), it is likely that fire activity in the early 20th century was indeed higher throughout the United States, due to extensive agricultural fires (15, 25), which are not depicted by our model. However, the overall correspondence between reconstructed and modeled past fire trends provides reasonable confidence in our future regional estimates in areas where precipitation projections are relatively robust [such as North America, Europe, and Australia (24)]. Nevertheless, it should be emphasized that although our projections agree with some regional studies (4, 26–28), they disagree with others (29), highlighting the uncertainty associated with estimating the future influence of climate and humans on biomass burning. We also cannot negate the possibility that future technological or methodological advancements will drastically improve fire suppression effectiveness, allowing reduction of fire activity to significantly lower levels.

Discussion

Although we have obtained quite reasonable agreement with reconstructed fire histories, our estimates of anthropogenic effects on global fires rely on highly incomplete information on fire-related human activities. Not only historical, but also comprehensive contemporary global data on anthropogenic ignitions and fire suppression are currently lacking. There is a need for comprehensive knowledge of worldwide anthropogenic fire management history, especially in the Industrial Period, to better resolve the role of humans in past fire activity, and more reliably assess their impact on future biomass burning. Nonetheless, these results present a major advance in biomass burning representation in climate models, reproducing the reconstructed millennium-long fire history. Our results indicate a precipitation-driven preindustrial fire regime, shifting to an anthropogenic-driven regime in the 18th century, and an imminent shift to a temperature-driven global fire regime in the future. This suggests a real possibility that fire management policies will have to adapt to a world in which climate plays a substantially stronger role in driving fire trends,

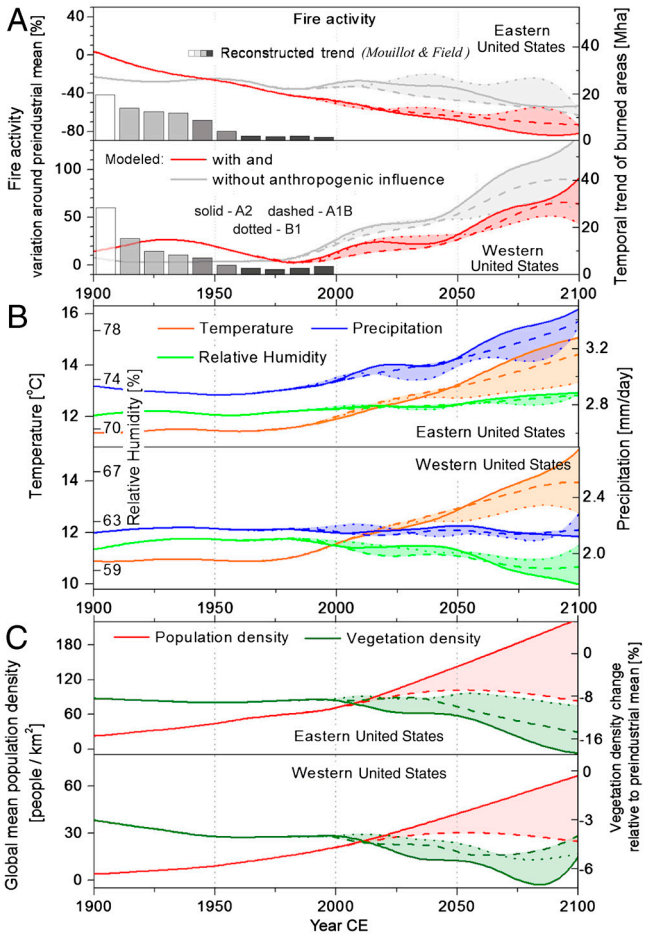

Fig. 4. Past and future fire activity, climate, vegetation, and population in the United States. Quantities are the same as in Fig. 2, but each plot shows two regions: the eastern (upper plots) and western (lower plots) United States. Bars show decadal reconstructions of temporal trends of burned areas for the two regions (25), which can be qualitatively compared with fire activity. Bar color indicates reconstruction reliability (25)—"accurate" (black), "good" (gray), "poor" (light gray), and "very poor" (white).

outweighing direct human influence on fire, a reversal from the situation during the last two centuries.

Materials and Methods

Fire activity estimates (see ref. 8 for detailed method description and evaluation) are based on temperature, precipitation, relative humidity, and lightning activity generated in AR4 GISS GCM climate simulations and HYDE (past) and Integrated Model to Assess the Global Environment (IMAGE) (future) land-cover and population density datasets. Climate during the 844–1880 CE simulations (9) was driven by variations in solar irradiance [responsible for the vast majority of multidecadal time-scale forced variability (30)]; 1880–2003 simulations (10) were driven by multiple forcings, including greenhouse gases, tropospheric aerosols, ozone, solar irradiance, and volcanic aerosols; 2004–2100 simulations (19) were driven by changes in the well-mixed greenhouse gases [the dominant climate forcing over the past few decades (19)]. Anthropogenic ignition sources are calculated as an increasing function of population density while assuming that people living in sparsely populated regions interact more with natural ecosystems and therefore produce potentially more ignitions (31). Fire suppression rates also increase with population density (8), with suppression rates kept constant at present-day level in regions with high population density (occurring relatively recently), whereas in the unpopulated areas no fire suppression is assumed at the beginning of the simulations, increasing to present-day levels by the 21st century, and remaining constant thereafter. Two alternative scenarios were calculated to characterize the uncertainty associated with our assumptions on past fire suppression rates (defining the boundaries of the red-shaded area in Fig. 1*A*); however, the general behavior of the global fire activity trends remained similar. *SI Text* provides further discussion of the setup of the simulations and the uncertainty associated with our assumptions on fire suppression rates, the contribution of individual model parameters to the fire activity trend, global fire activity variations vs. variations at the charcoal sites, zonal fire activity trends, and the data smoothing procedure.

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